Estuarine System Productivity: Lower Trophic Levels

REVISED DRAFT

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Introduction

This section addresses monitoring and research on system productivity. The "system" is defined as the Bay-Delta aquatic ecosystem which includes waters from the landward limit of tidal influence to the seaward limit of freshwater influence. It also includes the confluences of the numerous tributaries to the Bay-Delta, and tidal channels in wetlands (recommendations for those areas are also included in the shallow water monitoring section). "Productivity" includes the fundamental processes of primary production (conversion of inorganic carbon to biomass), and secondary production (growth rate times biomass of consumer organisms). In addition to the needs for monitoring primary and secondary production, this section addresses processes or environmental factors that may affect production, including basic hydrology and chemical variables. The types of monitoring and research addressed include physical processes, water quality (not including contaminants or human health), and the status of lower trophic levels (microbes, phytoplankton, aquatic plants, invertebrates not including decapod shrimp or crabs).

Goals and Objectives: This monitoring component addresses aspects of two related CALFED common programs: Water Quality and Ecosystem Restoration. It primarily addresses Goal 2 from the Strategic Plan for Ecosystem Restoration: *Rehabilitate the capacity of the Bay-Delta system to support, with minimal ongoing human intervention, natural aquatic and associated terrestrial biotic communities, in ways that favor native members of those communities.* To a lesser degree it addresses the Water Quality goal to *Provide good water quality for all beneficial uses.*

In addition, this section includes recommendations for several of the action items included in the Water Quality Technical Team's Stage 1 document related to salinity reduction, sediment reduction, and nutrients.

Approach: The approach to monitoring and research of system productivity is consistent with the monitoring principles listed in the Water Quality Chapter Introduction. We recommend that regular shipboard discrete monitoring be continued and expanded. We further suggest that this information be supplemented by the continued and expanded use of continuous telemetered water quality monitoring stations and possibly by data from remote sensing. We believe the proposed program can be expanded and adapted to assist with evaluation of the selected CALFED alternative when it becomes available.

Conceptual Framework

This element focuses mainly on open waters and tidal channels of the Delta and bays. Much of the information presented below comes from studies in Suisun Bay; differences among regions of the estuary are discussed below. More complete discussions of related conceptual models can be found in two technical reports published by the Estuarine Ecology Team (EET 1995, 1997).

The general conceptual model supporting this element rests on a fairly standard diagram of the food web of the estuary (Figure 1). This diagram depicts the major elements as boxes and the energy or carbon flows between them as arrows. A key part of the diagram is the shaded box surrounding most of the elements. This represents either some geographic region or some range of salinity, and means that the food web must be understood in the context of exchange processes between the region of interest and other regions further landward and seaward. Along with the exchange processes depicted there is a simultaneous exchange of all of the water-column components and some life stages of the benthic components. This exchange may occur passively (i.e., by advection and dispersion) or through active vertical or horizontal movement. Thus, movement of water (tidal and residual) along with sediment, nutrients, and living and detrital organic matter, is an essential feature of this ecosystem.

Primary production by phytoplankton and benthic plants (macro- and microalgae and vascular plants) within a geographic area provides one source of fixed carbon, while advection and mixing of organic carbon through the boundaries of the box provide the other. These subsidies can take the form of detrital or dissolved organic carbon or living organisms. Inorganic nutrients, required for plant and bacterial production, are supplied mainly by recycling from the food web, but also by inputs from the rivers and from the coastal ocean.

Primary production is apparently light-limited most of the time in most parts of the main estuary because of the high sediment concentration in the waters of the estuary (Cole and Cloern 1984, 1987). Therefore nutrients limit primary production only rarely, and sustained negative consequences due to eutrophication are not common in spite of high nutrient loading. However, some phytoplankton and other plant species may be nutrient-limited at times even though total production is not. Additionally, the relative importance of factors controlling primary production in the Delta is not well understood, and net primary production per unit area is probably greater in the Delta than in the main estuary. Eutrophication may have greater deleterious effects in the Delta than in other regions of the estuary. Following introduction of the clam *Potamocorbula amurensis* phytoplankton biomass in the brackish northern estuary declined precipitously (Alpine and Cloern 1992). Should the estuary's waters become clearer (e.g., through trapping of sediments in marshes), growth rates of phytoplankton populations would increase and eutrophication could become an issue.

The importance of the microbial food web (bacteria and microzooplankton) for higher trophic levels in the Bay-Delta is unknown. Bacterial production rate is high relative to primary production in the northern estuary (Hollibaugh and Wong 1996). Most bacterial production in other estuaries is consumed by protozooplankton, but grazing by microzooplankton is low, and protozooplankton are not abundant in the San Francisco estuary (Murrell and Hollibaugh1998). The high bacterial production must be consumed somewhere, possibly by the benthos (Werner and Hollibaugh 1993), and zooplankton could consume the large proportion of bacteria attached to particles in the brackish estuary (Hollibaugh and Wong in press).

Zooplankton and macrozooplankton (mysids and amphipods) feed on phytoplankton, other zooplankton, and other particulate matter. Species composition is a function of longitudinal position with regard to salinity (Kimmerer and Orsi 1996). Zooplankton abundance has declined since the 1970's. It declined sharply, and species composition shifted, following introduction of *P. amurensis* and several exotic species of zooplankton. Gelatinous zooplankton, important consumers of zooplankton in other estuaries, have not been studied.

The benthic communities of the San Francisco estuary are a melange of species from different parts of the world. The benthic community is primarily composed of worms, bivalves, and amphipods. These organisms feed off of organic matter in the sediment and plankton in the water column. The clam *P. amurensis* is particularly noteworthy in its striking effects on the rest of the ecosystem: following its introduction in 1986 and spread in 1987-88, phytoplankton, zooplankton, and mysid abundance declined sharply (Alpine and Cloern 1992, Kimmerer et al. 1994, Kimmerer and Orsi 1996, Orsi and Mecum 1996). In addition, the other components of the soft-bottom benthos may have been suppressed.

Most of the information on the lower trophic levels of the estuary is on abundance and (for phytoplankton and clams) biomass, and relatively little is known about the rates of population growth and the factors responsible for limiting primary and secondary production. This lack of knowledge of rates and limited information on biomass limits our ability to model carbon flow through the lower trophic levels. The applicability of the Cole-Cloern model of primary productivity (1984, 1987) to the Delta needs to be examined. Also, only a few measurements have been made of zooplankton reproductive rate (Kimmerer et al. 1994, Kimmerer unpublished), and none of growth rate of copepods or macrozooplankton. Secondary production by *P. amurensis* has been measured and related to chlorophyll concentrations. Otherwise, no other rates have been determined for benthos.

The topic of exotic species deserves special mention. Introduced species comprise a significant part or even a majority of the organisms collected in any part of the estuary by any method. The continual stream of new introductions ensures that the ecosystem will continue to change irreversibly. Any program of monitoring needs to be able to detect and chart the trajectory of newly introduced species. This may imply new sampling regimes such as that needed to sample mitten crabs, or expansion of existing regimes such as the large-scale spatial sampling that has been conducted for *P. amurensis.*

Differences among regions -- The various regions of the Bay differ in their lower trophic levels probably because of differences in physical characteristics of these regions. One important factor is the relative importance of tidal flows and net flows which depend on river inputs and exports. Tidal flows are the predominant mode by which water and substances move throughout the estuary. The further landward and the higher the freshwater flow, the greater the influence of net flow, although direct effects of freshwater flow are probably absent seaward of the LSZ (Burau 1998).

In the Delta, net and tidal flows are complex and, in the southern and central Delta, strongly influenced by export flow. Residence time and export flows appear to be important influences on phytoplankton biomass (Jassby and Powell 1994, Lehman 1996). The flux of chlorophyll between the Delta and the brackish estuary includes a seaward flux due to advection and dispersion, and a countervailing landward flux by which brackish-water phytoplankton are mixed into freshwater. The net dispersive flux, which was formerly close to zero (Jassby and Powell 1994), has probably increased since 1987 because concentrations are now much lower in regions affected by *P. amurensis*, i.e., brackish regions of the estuary. The Delta is usually characterized by fresh, highly turbid water with sometimes high phytoplankton biomass. Zooplankton and benthos are freshwater forms.

Suisun Bay is often the location of the Low-Salinity Zone (LSZ, formerly called the Entrapment Zone, Kimmerer 1998a). The LSZ has its own characteristic planktonic fauna. It is a transition region between freshwater and brackish water, and numerous chemical properties and several biological properties change sharply going seaward through this region. For example, the proportion of bacteria attached to particles increases in the LSZ (Hollibaugh and Wong in press). Food limitation of zooplankton in the northern estuary appears to be rare (Kimmerer et al. 1994), and striped bass larvae in this region were not found to be starving (Bennett et al. 1995). Delta smelt, however, appear to feed only on the copepod *Eurytemora affinis* which has been practically absent in this region in summer since 1987, so delta smelt may be food-limited.

Little is known of food-web conditions in San Pablo and Central Bays except for some monitoring data on benthos and phytoplankton, and some occasional work on zooplankton (Ambler et al. 1985, Kimmerer 1998b). Biota in these regions are probably affected strongly by high turbidity caused by wind and tide in shallow areas, particularly San Pablo Bay, and by gravitational circulation in the deeper channels. Typically salinity in Central and South Bay and even part of San Pablo Bay is near oceanic in summer and is depressed during high-flow periods.

The South Bay is a very different environment from the northern estuary. It is a lagoon with most of its freshwater entering from the northern estuary through Central Bay, which sometimes results in reverse estuarine circulation.

Exchange with the coastal ocean is arguably of great importance to conditions in the estuary, particularly closer to the mouth. However, there is little information on exchange processes.

Monitoring needs

General considerations Several attributes of the sampling program apply to many of the individual measurements and analyses suggested below:

- In general we recommend establishing continuous monitoring stations for physical and chemical variables with telemetered data in preference to, or supplemented by, shipboard sampling. This must be accompanied by an effective program of data management and assimilation into models (see Hydrodynamics).
- For shipboard sampling we recommend the continued use of CTD's (conductivity-temperature-depth instruments) with similar packages of associated instruments to include fluorometers, optical backscatter sensors (OBS), and dissolved oxygen sensors where needed.
- A study is needed of the effects of alternative sampling frequencies with regard to the spring-neap tidal cycle, and of the effect of sampling close to maximum flood vs. other sampling schemes.
- A coherent policy for storage and archiving of biological samples needs to be developed. Most of the samples that have been collected in the past have been discarded, with the loss of potentially valuable material for retrospective analyses. These samples can be particularly valuable in identifying and tracking new introductions.
- New techniques for sampling and analysis are continually becoming available. These need to be incorporated as they prove their utility. A current example is remote sensing: satellites are now flying that can provide information at useful resolution in terms of pixel size and wavelength. Remote sensing for chlorophyll and turbidity seems feasible (and is being tested in a pilot study at the Romberg Tiburon Center), and would provide vastly improved resolution of the spatial field of these key variables.
- The monitoring program must be prepared to detect and track newly introduced species, and in some cases to design and deploy new sampling methods for this purpose. This may include sampling in environments not currently sampled, such as

in shallow regions of the estuary and in and around shipping ports. In addition, it will require that personnel doing the identification either have adequate training in identifying novel species, or that they be trained to remove unidentified specimens from samples for identification by experts. Taxonomic keys used to identify regional species must include enough information to correctly exclude specimens not covered by the key, and prevent their misidentification.

Basic physical variables These attributes, also discussed in the Hydrodynamics element, are generally measures of habitat quality and in addition are essential for interpreting many of the biological variables. Most can be measured during routine shipboard sampling. Because of the CALFED emphasis on improving shallow water habitat for key species and for improving the quality of the channel and shoal habitats, it will be necessary to expand existing sampling coverage to those environments not now regularly sampled.

The efficiency of sampling and data processing of some physical variables would be greatly increased through the establishment of a system of continuous, *in situ* monitors that can provide hourly or more frequent observations, with data being automatically transmitted to shore stations. The technology for remote sampling of these variables already exists and, in fact, has been used on a limited basis in the estuary for many years. Such instrument packages should be installed in a large number of key, permanent locations throughout the bay-delta system. There are a number of such instrument packages within the Delta and at channel sites along the axis of the estuary (as part of compliance monitoring stations and salinity stations of the Interagency Ecological Program). The existing *in situ* monitoring sites need to be augmented, particularly in inadequately covered areas such as shallow areas, Delta sloughs, and the Yolo Bypass.

Climate variables The influence of climate on the ecosystem is pervasive, occurs through several mechanisms, and cuts across a variety of disciplines. Most of these data are collected by agencies outside of CMARP, so connections need to be made to ensure continuity of these data collections. These data include sea surface temperature, upwelling index, and basin-wide precipitation.

Meteorological measures These include wind speed and direction, air temperature, relative humidity, precipitation, and sunlight, used in measuring and modeling of water circulation and mixing, primary productivity, and suspended sediment transport.

Salinity This is a critical feature of habitat, useful as a tracer of water mixing, and is used in a standard that is achieved by controlling freshwater flow. Shipboard monitoring of salinity and other variables is done with CTD's which have become standard equipment for bay sampling. CTD profiles at shipboard sampling stations are generally used to provide a context for biological measurements, whereas continuous monitoring at fixed stations is used to provide information on the state of the physical system. At present, considerable confusion exists among scientists and engineers working in the estuary regarding the methods and units for reporting salinity. An analysis needs to be conducted to achieve consensus on the best ways to represent salinity and specific conductance, with the recognition that at low salinity the Practical Salinity Scale becomes undefined, and proportions of various ions begin to diverge from those of seawater.

Temperature This is also a critical habitat feature for all aquatic species because it regulates chemical and metabolic processes. Shipboard and *in situ* measurement should be as for salinity.

Suspended sediments/water clarity This provides a measure of the sediment load moving through the Bay-Delta system and is a controlling factor for water column primary productivity. As with salinity and temperature, a combination of shipboard and continuous sampling is necessary; however, sediment data are more difficult to interpret because sediments are highly non-conservative. Generally these measurements are made with OBS (optical backscatterance) instruments included with CTD instrument packages.

Light attenuation A measure of light availability for support of primary productivity, this should be monitored in routine shipboard sampling and can be derived from OBS sensors. However, Secchi disk readings should be continued for calibration with the historic data base.

Flow Variables These provide the essential underlying information defining the hydrologic environment of the Bay-Delta and thus for interpreting and analyzing data from the estuary, in particular within the Delta.

Total daily inflow Data should be provided from all tributary rivers and the Yolo Bypass

Diversion flows This should include export flow at the state and federal water projects, as well as flows at agricultural diversions within the Delta, including actual measures of gross removal and return flows

Tidal flows Data on tidal stage and velocity at various locations is essential for tying results of sampling runs to potential tidal influences.

Net (tidally-averaged) flows Flows at selected nodes are extremely useful for calibrating models and for understanding the movements of fish and substances. Flows within the Delta should be determined routinely, e.g., intake channel from Old River into Clifton Court Forebay, Grant Line Canal, Turner Cut, Columbia Cut or Middle River south of Columbia Cut, Connection Slough, and the San Joaquin River near Mandeville Island. In addition, techniques should be developed for measuring net flow rates at sites seaward of the Delta, e.g., at the confluence of the Sacramento and San Joaquin Rivers, at Chipps Island, Montezuma Slough, New York Slough, Carquinez Strait, and the Golden Gate. Additional sites should be selected that would be relevant to the CALFED alternatives for structural changes in the Delta flow regime

Chemical Measurements

pH This variable is routinely measured in studies of freshwater environments, as it can be diagnostic of acidification problems. It is not very useful in marine or brackish systems (except that it is necessary in primary productivity measurements), or when there is not a problem with acid-base chemistry. This variable should be monitored on a routine basis during other routine sampling in freshwater only.

Dissolved Oxygen Low dissolved-oxygen concentrations can affect the health of aquatic organisms and impede migration of fish. Low dissolved oxygen concentrations are a good indicator of eutrophication, a common condition in estuaries in which high nutrient loading produces excess respiration following phytoplankton growth. Although eutrophication has not been a problem in this estuary, low dissolved oxygen concentrations are routinely measured in the Stockton Ship Channel in the fall, where high amounts of effluent, storm water runoff, redox reactions, phytoplankton biomass, and water temperature combine with low streamflow. If the estuary continues to become clearer, problems of eutrophication and hypoxia may increase as phytoplankton production increases. This, combined with the low cost of these measurements, suggests continual sampling using oxygen sensors mounted on CTD's used for profiles in routine monitoring, and continuous monitoring in the San Joaquin River. Data should be reported both as concentration and percent of the saturated value for the temperature.

Nutrients The "macronutrients" required for growth by the phytoplankton and submerged aquatic vegetation comprise several forms of nitrogen (nitrate, NO_3^-; nitrite, NO_2^-, and ammonium, NH_4^+), phosphate ($PO_4^{=}$) and silicate. Additional trace nutrients commonly measured in oceanographic sampling (e.g., iron) are probably present in the estuary at high concentrations relative to the requirements of plants. Nutrients apparently become limiting only during blooms, so nutrient concentrations are not very informative. Nevertheless, because they are important indicators of growth conditions for plants, nutrients should be measured during routine discrete sampling cruises.

Organic nutrients Total N and P are not now routinely measured. They are more expensive to determine than inorganic nutrients and can be difficult to interpret. However, these measurements do give useful information about the nutritive status of the estuary, particularly when compared to inorganic nutrient concentrations. Therefore these should be measured, but at fewer stations than the inorganic nutrients and with the intent to stop monitoring them after several years if they do not prove informative.

Organic carbon Total and particulate organic carbon (the difference being dissolved organic carbon) indicate the organic matter present in two size fractions. However, these measurements include both labile (readily available) and refractory carbon, the latter being material that has a long biochemical residence time and probably does not react much within the estuary. Thus these measurements do not indicate what is available for consumption by heterotrophic organisms, although their relative amounts could be informative about the food web. An alternative is long-term BOD (biochemical oxygen demand) which can be highly variable but gives a result that should be close to the amount of labile carbon (Carlson and Ducklow 1996). Since this has not been routinely measured, a pilot study should be conducted.

Primary producers

Phytoplankton biomass The biomass of phytoplankton is an indicator of the quantity of food energy (carbon) available to fuel the food web. Excessive phytoplankton biomass can suggest eutrophication. Phytoplankton biomass is routinely measured as chlorophyll *a* concentration. This can be measured by extraction and fluorometric or spectrophotometric analysis, or estimated by in situ fluorescence calibrated with extracted chlorophyll. Routine measurements of chlorophyll should be made using fluorometers with calibration using extracted samples at each of the sampling stations. However, two additional variables can be useful. First, the food of copepods is best estimated as chlorophyll larger than some minimum size (e.g., 11 μm, Berggreen et al. 1988), which suggests that size-fractionated chlorophyll should also be measured. Second, phaeopigments, the degradation products of chlorophyll, can be useful as a measure of the status of phytoplankton or to indicate qualitatively the degree to which the chlorophyll is being grazed. Thus, at each shipboard station a vertical fluorescence profile should be taken along with a single sample for chlorophyll and phaeopigments (whole and >10μm), and continuous subsurface fluorescence data should be taken between stations.

Phytoplankton primary production To assess the dynamics of carbon production for higher trophic levels, one needs to know both the biomass of the phytoplankton and the rate at which they are producing biomass. An empirical model that predicts the rate of primary production from measures of phytoplankton biomass, light, and light attenuation rate (Cole and Cloern, 1987) is applicable to a number of estuarine systems. Its application to the Delta must be verified for the range of conditions in this system. If the model is generally applicable to the Delta, then primary production rates need be measured routinely at only a few stations to continue to validate the model.

Phytoplankton species Phytoplankton species abundance and biomass by species are important characterizations of the phytoplankton community. Species composition provides information on the response of the phytoplankton to environmental conditions and the quality of food available to organisms at the base of the food web. Further, it can indicate the presence of newly introduced or abundant species that are toxic, harmful or undesirable (e.g., *Pfesteria piscicida* and *Pseudonitzschia spp.*) for humans or the food web. The composition of the freshwater phytoplankton community provides an indicator of potential problems with taste and odor in drinking water. Species composition is determined by microscopic counts, and cells are measured to obtain estimates of biomass by taxonomic group.

Benthic microalgae The role of benthic microalgae in supplying fixed carbon to the ecosystem is unknown, yet the extent of shallow water suggests they may be important. In addition there may be a dynamic exchange of cells between the bottom and the overlying water column. This suggests the need for some research on the role of these organisms, which will be needed to develop a comprehensive understanding of carbon flow in the system.

Submerged aquatic vegetation (SAV) In many estuarine ecosystems vascular plants, seagrasses, macroalgae, and their epiphytes are important primary producers and provide important habitat for fish and invertebrates. SAV is clearly important in the Delta in providing or altering habitat, and it may also play a significant role in carbon flow. Many of the prominent SAV organisms are introduced (e.g., *Egeria*, water hyacinth), while some natives are important and were once much more abundant (e.g., tule). Little is known of SAV in the brackish estuary. Although seagrasses appear uncommon, and substrates suitable for macroalgae may be rare, an assessment needs to be made of the extent and importance of these forms, both as producers and as habitat.

Microbial communities

Bacterial counts, biomass, and metabolic rate These measurements should be made periodically but probably not as part of a continual routine monitoring program. A series of measurements made every quarter may suffice, or in alternate years. Although bacteria are probably a very important part of the Bay's food web, the measurements are somewhat difficult and require specialized expertise. ATP (adenosine triphosphate) can be a useful routine measure of total living planktonic biomass, from which bacterial biomass can be determined by difference (by subtracting chlorophyll-containing and microzooplankton biomass).

Zooplankton

Mesozooplankton : These are moderately small zooplankton including copepods, cladocerans, and rotifers. Analysis of the abundance and biomass of these forms will be essential as basic variables describing the state of the food web. Suitable variables to determine on these communities include abundance by species (per m^3), biomass (mg/m^3), and length or life stage composition including presence of eggs in egg-carrying species. Biomass can be determined using relatively few measurements of weight per stage or length-weight relationships.

Macrozooplankton This includes mysids and amphipods, both essentially epibenthic forms that are collected in coarse-mesh plankton nets. These species are important food for a variety of young fish, hence the need to monitor their abundance. Sampling for these species could be combined with that for larval fish if the latter samples are taken near the bottom. Variables should include abundance by species, biomass, and size composition.

Microzooplankton This includes rotifers, protists, and larval copepods. These are very important in aquatic food webs, often dwarfing the larger zooplankton in consumption and metabolic rate. Their abundance should be monitored, but to date only the rotifers and copepod larvae have been monitored. The smaller microzooplankton (protozoa and heterotrophic microflagellates) have not previously been monitored; it seems that the widely-accepted "microbial loop" conceptual model has failed so far to resonate with much of the Bay-Delta scientific community. Therefore a pilot study should be set up to assess abundance and biomass of these organisms and to design a monitoring element.

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Gelatinous zooplankton Jellyfish, ctenophores, and other gelatinous forms can be important predators on crustacean zooplankton and larval fish. Most of these species occur in brackish to salt water, and some are apparently confined to inshore areas. In open waters they are occasionally common, and should be monitored in combination with studies of predation rates to allow a calculation of their predatory impact.

Zooplankton secondary production Production of animals, the rate at which food is made available to fish and other larger animals, is essentially the product of biomass and specific growth rate (or fractional daily growth in weight). Typically most of the variation in secondary production is attributable to changes in biomass, whereas growth rate varies much less. This suggests production could be determined by combining frequent biomass measurements with less frequent determinations of growth rate.

Sediment Quality

Sediments are generally monitored to describe benthic habitat. Together the variables listed can be used to evaluate the suitability of habitat for benthic species. Measurements of carbon, nitrogen, sulfide, and ammonia are also useful for parameterizing and validating modeling studies. When monitored synoptically with response indicators such as benthic invertebrates, mysids, or fish, these measurements may be useful as environmental predictor variables.

Sediment grain size Measurements of proportions of gravel, sand, silt, and clay are used to describe sediment composition. Grain-size information is also used to deduce physical processes such as deposition or erosion. It is associated with the capacity of sediment to bind certain contaminants, especially trace metals.

Total organic carbon (TOC) The carbon content of sediment is used to describe the nutritional content of sediment, largely from detrital breakdown, but also from flocculation of dissolved organic carbon. It is also an important determinant of certain trace organic contaminants that adsorb onto organic carbon.

Total nitrogen C:N ratios describe the general nutritional composition of sediment.

Total sulfide (or hydrogen sulfide). The amount of sulfide in sediments is a direct result of the reducing or oxidizing capacity of sediments. Hydrogen sulfide is toxic to organisms.

Un-ionized ammonia Ammonia is toxic and may confound development of natural benthic communities.

pH This is used to determine suitability for habitat and as a determinant for geochemical reactions. For example, pH is used in calculations of hydrogen sulfide from total sulfides.

Benthic Fauna

Here and elsewhere around the world it has been demonstrated that benthic community composition can be used as a reasonable proxy for documenting changes in lower trophic level aquatic community structure and secondary productivity, and as a water quality "sentinel." These organisms are important because (1) they are an important trophic step between living and detrital particulate organic matter and higher trophic levels including fish, birds, and people; (2) they contribute to the flux of dissolved and particulate material (including contaminants) between the sediment and the overlying water; (3) the types and abundance of benthic animals and their variation are commonly used as indicators of water quality; and (4) the benthos of coastal aquatic systems is particularly susceptible to invasions of exotic species released from ballast water. Because most benthic organisms do not move far after settlement, the benthic community provides a continuing record, through changes in species composition or abundance, of the effects of both short- and long-term changes in the environment

Species composition and abundance Short- and long-term changes in the macrobenthic (>0.5 mm) community often show clear responses to environmental conditions such as salinity and temperature. These responses are species-specific, so the variability of individual species provides useful information.

Biomass The biomass of major phylogenetic groupings and dominant species can be determined with relatively little additional effort above that needed to collect samples for abundance. This information is essential for inserting benthos into models of carbon flow in the system.

Size distributions of dominant species Sizes are useful for estimating biomass, and also for estimating growth rate by the cohort method. This leads to calculations of secondary production for the dominant species, and estimates of total secondary production by the benthic community.

Current Monitoring Activity

At least 5 major monitoring programs currently address aspects of system productivity in the Bay- Delta (Table 1). Not all variables recommended above are currently monitored, and not all variables monitored are covered throughout the system. Nevertheless, a substantial basis exists for this CMARP element.

Water chemistry and nutrients are monitored by all programs, but not necessarily the same individual variables. Further, they all use different methods of collection and analysis. None of the current program monitors microbial or macrophyte communities. Nearly all of the D1485 monitoring for lower trophic levels and water quality focuses on the Delta to Suisun or San Pablo Bay, and USGS monitoring focuses mainly on South Bay, although with monthly cruises through the entire estuary as far as Rio Vista. San Pablo and Central bays are poorly monitored.

Since those programs were each designed independently to address their respective objectives, it is not surprising that they are not very well coordinated. However, they form an excellent basis for CMARP. Augmented modestly, these programs could readily be adapted to serve CMARP's purposes. This would require additional planning, collaboration, and calibration among the programs.

One good example of such collaboration is for benthic monitoring. Both IEP and RMP currently monitor benthos. IEP monitors in the Delta into San Pablo Bay on a monthly schedule. The RMP monitors in San Pablo to South Bay semiannually. Each year the data are combined, the taxonomy is standardized and the data are analyzed together to obtain an assessment of benthos throughout the Bay and Delta (Thompson *et al*. 1997, 1998). Similar collaboration and coordination could be affected for other system productivity components.

Research Needs

Monitoring is insufficient to develop the level of understanding of the estuarine system expected of CMARP. Monitoring supplies information on trends and patterns in abundance, distribution, and other variables measured, but cannot determine cause and effect, nor can it be used in prediction. Research must be sufficient to elucidate the processes governing the variation discovered by the monitoring programs, and must be used both to interpret the monitoring results and to predict future system changes resulting from management actions.

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The following discussion of research needs has been assembled from the recommendations of team members. These are not presented in order of importance.

1. **Revisit the flow-X2 relationship and update it.**

   The existing relationship between X2 and flow was developed using a limited subset of the available data and has not been updated since originally formulated in 1992. Since X2 has become a key indicator of the physical response of the estuarine ecosystem to freshwater flow, it should rest on firmer footing. This is a relatively small, but important, research project.

2. **Develop carbon and nutrient budgets for the estuary and its sub-regions.**

   Justification: The estuarine ecosystem runs on fixed carbon, and production and consumption imply proportional fluxes of nutrients. These concentrations and fluxes set upper limits for production at various levels in the ecosystem. A relatively straightforward budget would provide some of the bounds for production, which could be used to assess the scope for further restoration. In addition, the contribution of carbon flux in the Bay/Delta system to global fluxes could be assessed. Budgets would be calculated using both flux measurements through system boundaries (see Hydrodynamics) and system-wide calculations of material budgets.

   Further justification for monitoring carbon and understanding the carbon budget relates to the importance of carbon to formation of disinfection byproducts (See Drinking Water Quality section).

3. **Develop models of phytoplankton dynamics for the estuary and its sub-regions**

   Phytoplankton are one of the principal sources of organic carbon (food) for higher trophic levels in the Bay and Delta. Phytoplankton production is controlled by nutrient dynamics, hydrodynamics, and physical factors that vary on temporal and spatial scales that make these relationships difficult to observe directly. This suggests a program to develop linked hydrodynamic - nutrient models of phytoplankton dynamics in the Bay - Delta to help explain how potential changes in geometry, nutrient loadings, and flows will affect phytoplankton populations. Some of this work is already in progress in the USGS study funded under Category III; however, it should be augmented to examine species composition of phytoplankton and how it varies with environmental conditions.

4. **Determine the relative importance of various organic carbon sources in the northern estuary.**

   Justification: bacterial production greatly exceeds primary production in the northern estuary (see conceptual model), suggesting an exogenous source of carbon. The origin of that carbon may be freshwater phytoplankton, or it may be living or detrital carbon originating in rivers or their watersheds, marshes, or the Delta. The importance of this exogenous carbon is heightened by the reduction in chlorophyll implying a reduction in local primary production in the brackish regions of the estuary since the spread of *P. amurensis* . The source of carbon is important because different management actions (e.g., increases in marsh or upstream riparian habitat, changes in residence time of the Delta) may have influences on different carbon sources. For example, if most of the carbon comes from freshwater phytoplankton, then changes in residence time of the Delta are likely to have a greater influence by stimulating freshwater phytoplankton production than changes in riparian or marsh habitat. (Note: some or all of this may be in progress under the USGS-led research project currently funded by Category III).

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Different food web components may use different organic carbon sources. For example, benthic organisms may use different food from the various categories of zooplankton. The sources of carbon should be determined for each.

5. **Determine the fate of bacterial production in the northern estuary**

   Justification: High bacterial production (relative to primary production) is apparently not being consumed by protozoa in the northern estuary (Murrell and Hollibaugh 1998). How much of this production contributes to production in higher trophic levels depends on the pathways by which it gets there. It must be consumed, since bacterial biomass is not steadily increasing. Alternative consumers include clams, rotifers, and copepods. Of these, clams no doubt consume a lot of biomass but are unlikely control agents because of the extreme mismatch in generation times with bacteria (months vs. days). Rotifers can have a rapid numeric response and could be major consumers of bacteria. Copepods are unable to consume bacteria directly but could consume bacteria-rich organic aggregates that provide habitat for a large fraction of the bacteria in the Low-Salinity Zone and seaward (see Conceptual Model). Each of these consumers provides food for different parts of the food web, with copepods providing the most direct link to young fish.

6. **Continue and expand work on retention mechanisms in the Low-Salinity Zone and seaward**

   Justification: Conceptual models of the LSZ have been changing, but this region is still a key habitat for a number of species including young striped bass and delta and longfin smelt. The Entrapment Zone study showed that all species resident in the LSZ undergo tidal vertical migration that tends to reduce their seaward movement. However, not all migrate sufficiently to offset the net seaward flow. This implies either that lateral processes predominate, or that gravitational circulation occurring in deeper areas of the estuary influence the retention of these organisms. The importance of this is related to the effects of X2 on abundance of certain LSZ species (e.g., mysids). In addition, the advantages of LSZ residence are unclear; this implies a need for physiological (e.g., salinity tolerance) studies as well as investigations of the role of turbidity and the availability of organic particles in the LSZ. Since similar mechanisms probably work seaward of the LSZ, these should be investigated as well. This research topic will require close coordination with salt and material flux studies in the Hydrodynamic element.

7. **Assess the role of benthic microalgae in the estuarine food web**

   Justification: It has been assumed that phytoplankton are the major producers in the estuarine food web. However, the vast areas of shallow mudflat and marsh habitat suggests that other producers may be important too. The carbon flux from these sources needs to be assessed in relation to phytoplankton production; if a significant contributor, methods for monitoring this input need to be developed.

8. **Model studies of the food web**

   At present we do not have sufficient information to develop even simple models of the estuarine food web. However, for certain taxonomic groups, notably the zooplankton, benthos, and fish, we have information on abundance patterns and could develop estimates of biomass and production. This should allow us to generate carbon flow models that would help to determine the major sources and sinks, and considering changes over time would allow for the estimation of how management may affect the estuarine food web, e.g., through changes in Delta geometry or flow management.

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9. **Study of the role in the food web of introduced zooplankton species**

Justification: Numerous introduced zooplankton species now occupy habitats formerly occupied by natives. These species differ from the natives in numerous ways that may include their suitability as food for higher trophic levels. For example, striped bass larvae feed more successfully on the native (or long-term naturalized) copepod Eurytemora affinis and are less successful at capturing the introduced Sinocalanus doerrii. Similarly, delta smelt feed almost exclusively on E. affinis and much less on the introduced Pseudodiaptomus forbesi. In addition, the numerically dominant copepods Limnoithona tetraspina and L. sinensis are much smaller than the native species and may be less suitable as food. Thus, a program of research is needed to assess how these "new" species may influence or even impede the trophic transfer of energy up the food web. If this preliminary evidence is borne out, the presence of these introduced species could reduce the effectiveness of management actions intended to bolster food webs in the estuary.

10. **Continue studies of the influence of *Potamocorbula amurensis* on estuarine food webs.**

Justification: *P. amurensis* may be the single biggest impediment to restoration of food webs of the brackish estuary. It is certainly a major factor in the food webs of the estuary. Although considerable work has been done and continues on this species, there is a lot more we need to know. Topics include the extent to which this clam is responsible for the observed decreases in phytoplankton and zooplankton, its effect on other benthic species, the importance of various food sources to *P. amurensis*, and the effect of the clam on material cycling (sediments, nutrients, carbon) all need to be investigated.

11. **Anticipate the role in the food web of additional introductions of exotic species**

The ERP Strategic Plan calls for steps to minimize the risk of future introductions, owing to their potentially disastrous effects. Nevertheless, introductions of exotics will continue, although we hope at a reduced rate. It is inherently difficult to anticipate the future influence of exotic organisms that have not yet been introduced, but by understanding the structure of existing systems, we may be able to anticipate the vulnerability of the Bay-Delta ecosystem to additional invaders. Is there a freshwater boring clam that will attack piers and pilings above the low-salinity zone? Is there an unpalatable planktonic predator that could suppress copepods of importance to larval fish? Can we rule out the invasion of an organism such as *Pfiesteria?*

12. **Determine the roles of benthic invertebrates and various size classes of zooplankton in the food web leading to species targeted for restoration**

Justification: Many of the fish and invertebrate species that are likely to be selected for restoration efforts are likely to be food limited at least some of the time. The location, duration, and severity of food limitation is critically important in regulating population size, but is poorly known for the species of the estuary. Yet, this could have profound implications for restoration. For example, *P. amurensis* has apparently caused a great reduction in the abundance of food organisms for Delta smelt, while it may itself be a significant food source for some species. This suggests research on the degree to which the benthos "controls" the pelagic food supply, and the extent to which that makes conditions favorable or unfavorable for planktivores or benthivores.

13. **Sediment Studies:**

a. Estimate loadings of sediments from the mainstem rivers into the Bay and Delta.

b. Determine deposition rates, residence times, and burial rates for sediments in representative habitat types in the Bay-Delta.

Justification. The sources of sediments for the Bay-Delta are believed to be erosion and resuspension during wet weather and high flows in the rivers (Porterfield, 1980), although retention times in the estuary are long and sediments from hydraulic mining are still in the bay (Krone 1979). The frequency and duration of loading events, residence times, deposition, and burial rates have not been well studied. Knowledge about source, loadings, and fate and transport of sediments from the rivers into the Delta and bay are important for management of the system. Understanding of those processes will allow managers to identify source intervention strategies and would inform managers about the use and stability of sediments in critical restoration areas. In addition, the movement through the system of sediment-bound contaminants depends on the movements of the sediments.

14. **Determine benthic production in each major habitat.**

Justification: Studies of benthic production represent an important component of overall system productivity, especially as related to food for fish. Numerous species of fish (e.g., salmon, striped bass, starry flounder, sturgeon) consume benthos. It is important to understand anthropogenic vs. natural causes of variability in benthic production, abundance, species and composition. Information of this sort is essential for understanding and modeling the ecosystem, and for making informed choices about flow and salinity patterns, reduction of contaminants, and structural changes.

15. **Determine the effects of shallow water restoration projects on primary production.**

Justification: Current restoration plans for the estuary include establishment of extensive shallow water habitat. Presumably this habitat will support fish as well as producers such as marsh plants, phytoplankton, and phytobenthos. At present the importance of this production to the estuarine system cannot be predicted. Thus, the degree to which shallow habitat increases production, and the response of this production to environmental conditions, needs to be examined.

16. **Determine the importance of sediment and nutrients to production of phytoplankton and aquatic plants.**

The San Francisco Bay Estuary is characterized by high nutrient concentrations that in many estuaries would be associated with eutrophication. The absence of eutrophication has been attributed to high water-column sediment concentration that limits light needed for phytoplankton growth. Long-term increases in water transparency and long-term CALFED goals to reduce sediment and nutrient load plus changing streamflow may alter the existing balance between sediment and nutrient concentration in the estuary. Research is needed to determine the influence of sediment and nutrients on both algal and higher aquatic plant growth and how these should be managed to prevent eutrophication.

17. **Determine factors that control higher aquatic plant growth in the estuary.**

Higher aquatic plant production (e.g., water hyacinth) has increased to nuisance proportions in some areas of the estuary. Research is needed to determine the physical, chemical and biological factors that control their growth and distribution in the estuary and their effect on estuarine fishery resources. Information is also needed on how on-going restoration projects may affect their growth and distribution.

18. **Research in support of monitoring**

Justification: a number of variables considered for monitoring were not selected for the routine program because of lack of (or our unfamiliarity with) suitable methods or because the importance of the variable proposed was unclear. The following pilot monitoring or research programs are suggested:

a. For all of the major monitoring elements, conduct a study of sampling frequency and station spacing, and assess the effects of sampling on different tidal stages.

b. Conduct pilot monitoring studies for potentially significant foodweb components not now being monitored (see Table 1).

c. Develop a consistent nomenclature and reporting system for salinity and specific conductance.

d. Assess the suitability of ATP (adenosine triphosphate) as a measure of microbial biomass.

e. Conduct a pilot study of BOD (biochemical oxygen demand) as a measure of the availability of organic carbon.

f. Develop techniques for monitoring protozooplankton and incorporate these in the routine monitoring program.

g. At intervals determine growth rates and weights of zooplankton to allow secondary production to be estimated routinely from abundance data.

h. Conduct and expand pilot studies to incorporate remotely sensed data into a manageable reporting and analysis scheme.

Indicators

All of the variables considered for monitoring here could be considered as indicators. None of them is particularly useful as a high-level indicator, i.e., one that demonstrates movement toward CALFED goals. This may change as the system develops. Several variables may be useful as intermediate-level indicators of estuarine productivity, notably primary production and exogenous carbon input. However, these should be interpreted with caution because their magnitudes are not monotonically associated with any benefit to the ecosystem.

Links

Links to other elements are listed in Table 2. The most important links are to the Hydrodynamics element and all of the elements relating to fish and macroinvertebrates in the estuary.

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Table 1. Summary of variables recommended for monitoring program. For each variable an indication is given whether routine monitoring is recommended, whether current monitoring covers the entire estuary, and which programs conduct monitoring, if any. Symbols indicate whether monitoring is recommended or is being done (Y), or whether pilot studies (P) or targeted research (R) are needed or being done. Existing programs include **D** 1485 compliance monitoring (IEP), Sacramento **C**MP, **S**acramento River watershed, **U**SGS, and SFEI **R**egional Monitoring Program. * Flow variables are collected from a variety of sources and made available through the DWR DAYFLOW program. ** Zooplankton monitoring is being extended into the lower bays in a pilot study. Size distribution and biomass for *P. amurensis* only.

	Monitoring	**Complete**	**Programs**				
Variable to be Monitored	**Recommended**	**Coverage**	**D**	**C**	**S**	**U**	**R**
Basic Physical variables							
Meteorological measures	Y		Y			Y	
Salinity	Y		Y	Y	Y	Y	Y
Temperature	Y		Y	Y	Y	Y	Y
Suspended sediments/water clarity	Y		Y			Y	Y
Light attenuation	Y					Y	
Total daily inflow	Y .	N*	Y				

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Diversion flows	Y	Y*	Y				
Net (tidally-averaged) flows	Y					R	
Water chemistry							
pH	Y (Freshwater)		Y				Y
Dissolved Oxygen	Y		Y			Y	Y
Nutrients	Y		Y	?	?	Y	Y
Organic nutrients	N		Y				
Organic carbon	Y					Y	Y
Primary producers and bacteria							
Phytoplankton biomass	Y		Y			Y	
Phytoplankton primary production	Y						
Phytoplankton species	Y		Y			Y	
Benthic microalgae	P						
Submerged aquatic vegetation (SAV)	P						
Bacterial counts, biomass, and metabolic rate	P						
Zooplankton							
Mesozooplankton:	Y	P**	Y				
Macrozooplankton	Y	P**	Y				
Microzooplankton	P						
Gelatinous zooplankton	P						
Zooplankton secondary production	P						
Benthos and sediments							
Sediment grain size	Y		Y				Y
Total organic carbon (TOC)	Y		Y				Y
Total nitrogen	Y						Y
Total sulfide (or hydrogen sulfide).	Y						Y

	Un-ionized ammonia	Y						Y
	pH	Y						Y
	Species composition and abundance	Y		Y		Y	Y	Y
	Biomass	Y		Y			Y	Y
	Size distributions of dominant species	Y		Y			Y	

Table 2. Links between the Lower Trophic Level element and other CMARP elements

Program	Nature of Link
Hydrodynamics	Coordination of modeling efforts, field sampling programs
Fish-X2	Provide data to that element
System Productivity: fish/inverts	Coordinate monitoring stations, field sampling programs. Provid data on lower trophic levels to that element
Contaminants	Sampling design, particularly for sediments; water and sediment movement
Data management	Data transfer
Targeted research	Unknown, depends what develops